IJCRM

International Journal of Contemporary Research In Multidisciplinary

Research Article

Influence of Heliospheric Solar Wind Features on Periodic and Transient Cosmic Ray Variations Across Solar Cycle 24

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DOI: https://doi.org/10.5281/zenodo.20036604

Abstract

This study investigates the long-term modulation of Cosmic Ray Intensity (CRI) in relation to heliospheric parameters during Solar Cycle 24 (2008-2019), using daily averaged neutron monitor data in conjunction with near-Earth solar wind observations. The analysis focuses on the role of the Interplanetary Magnetic Field (IMF) and key solar wind parameters, including solar wind speed (Vsw), dynamic pressure (Pdyn), and proton density (Np), in controlling CRI variability.

The results reveal a clear inverse relationship between CRI and IMF magnitude, with a correlation coefficient of $r = -0.342$ indicating that IMF is the most significant parameter influencing long-term cosmic ray modulation. During solar minimum periods (2008-2009 and 2018-2019), IMF values decreased below 4 nT, corresponding to enhanced CRI levels, whereas during solar maximum (2013-2015), IMF increased to 6-8 nT, leading to a marked suppression of CRI. In contrast, solar wind parameters exhibit comparatively weak correlations with CRI: solar wind speed ($r = -0.164$), dynamic pressure ($r = -0.141$), and proton density ($r = +0.045$), indicating their limited contribution to long-term modulation. Spectral analysis using Fast Fourier Transform (FFT) shows a dominant peak at low frequencies, confirming that CRI variability is primarily governed by long-term solar cycle periodicities (11 years). Cross-correlation analysis further indicates a strong anti-correlation between CRI and IMF with a short response time of approximately 0-3 days, suggesting rapid modulation of cosmic rays by heliospheric magnetic field changes.

Overall, the study demonstrates that heliospheric magnetic field conditions, particularly IMF strength, play a dominant role in regulating cosmic ray intensity near Earth, while solar wind plasma parameters contribute only marginally. These findings are consistent with established cosmic ray transport theory and have important implications for space weather forecasting and radiation environment modelling.

Manuscript Information

- **ISSN No:** 2583-7397
- **Received:** 03-04-2026
- **Accepted:** 28-04-2026
- **Published:** 05-05-2026
- **IJCRM:**5(3); 2026: 27-36
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- **Plagiarism Checked:** Yes
- **Peer Review Process:** Yes

How to Cite this Article

Tiwari C M, Ojha L, Pandey J, Parsai M K, Gautam D, Pandey A, Tiwari S K. Influence of heliospheric solar wind features on periodic and transient cosmic ray variations across Solar Cycle 24. Int J Contemp Res Multidiscip. 2026;5(3):27-36.

Access this Article Online

www.multiarticlesjournal.com

KEYWORDS: Cosmic Ray Intensity, Neutron Monitor, Solar Wind, IMF, Solar Cycle 24.

1. INTRODUCTION

The modulation of Galactic Cosmic Rays (GCRs) within the heliosphere is a well-established phenomenon that plays a central role in space weather and heliospheric physics. The theoretical foundation for this process was laid by Eugene Parker (1965) [1], whose transport equation describes the combined effects of solar wind convection, magnetic diffusion, particle drifts, and adiabatic energy changes. Over time, both observational and theoretical studies have advanced our understanding of how solar wind parameters govern these transport mechanisms, with recent studies further emphasizing the coupling between heliospheric dynamics, geomagnetic activity, and cosmic ray variability [18, 22].

The total scalar magnitude of the Interplanetary Magnetic Field (IMF, B) has long been recognized as a key factor in long-term cosmic ray modulation. Potgieter (2013) [2] demonstrated that the diffusion coefficient of cosmic rays is strongly dependent on IMF strength and turbulence levels. An increase in IMF intensity enhances magnetic scattering, thereby reducing the mean free path of cosmic rays and limiting their penetration into the inner heliosphere. Similarly, Badruddin and Kumar (2015) [3] reported a strong anti-correlation between cosmic ray intensity and heliospheric magnetic field strength across multiple solar cycles, reinforcing the dominant role of IMF in controlling long-term GCR variability. Recent investigations have also highlighted how variations in geomagnetic field conditions and solar wind–magnetosphere coupling further influence cosmic ray intensity profiles [21].

Short-term variations in Cosmic Ray Intensity (CRI), particularly Forbush decreases (Scott E. Forbush, 1937) [4], are primarily associated with transient solar wind structures. Cane (2000) [5] and Richardson (2004) [6] classified these disturbances into Interplanetary Coronal Mass Ejections (ICMEs) and Corotating Interaction Regions (CIRs). Their studies showed that sudden increases in solar wind speed (Vsw) and dynamic pressure (Pdyn) act as effective convective barriers, sweeping cosmic rays outward from the inner heliosphere. Further investigations by Belov et al. (2014) [7] emphasized that the most intense Forbush decreases occur when high-speed solar wind streams are accompanied by strongly compressed magnetic fields, indicating a combined kinematic and magnetic control on transient CRI suppression. In addition, recent studies of solar energetic particle (SEP) events associated with CMEs have provided further insight into transient modulation processes and particle transport dynamics [19, 20].

Solar Cycle 24 represents a unique heliophysical case due to its significantly reduced solar activity. McComas et al. (2013) [8] reported that this cycle exhibited the lowest solar wind dynamic pressure, weakest IMF strength, and reduced plasma density recorded in the space age. As a consequence, Mewaldt et al. (2010) [9] observed historically high cosmic ray intensities near Earth, attributed to enhanced diffusion conditions and weakened heliospheric shielding. Additionally, Hathaway (2015) [10] highlighted that reduced solar polar magnetic fields altered particle drift patterns, further influencing cosmic ray propagation during this cycle. Recent event-based studies have also examined cosmic ray enhancements linked to specific solar disturbances, providing case-based validation of modulation processes [23].

Traditionally, studies of cosmic ray modulation have relied heavily on solar activity proxies such as sunspot number (SSN) and F10.7 solar radio flux (Ross & Chaplin, 2019) [11]. While these proxies provide valuable long-term trends, they do not directly represent the physical processes governing cosmic ray transport. Aslam and Badruddin (2012) [12] emphasized the importance of using direct in situ solar wind and IMF measurements to better capture the dynamic interactions within the heliosphere. The anomalous nature of Solar Cycle 24, where conventional SSN-CRI relationships weakened, further underscores the need for such an approach, particularly when combined with modern analyses of geomagnetic storms and space weather effects [22].

In this context, the present study builds upon this evolving paradigm by focusing exclusively on in situ interplanetary parameters. By leveraging the uniquely weak heliospheric conditions of Solar Cycle 24, this work aims to isolate and quantify the relative efficiency of solar wind kinematics and magnetic field properties in modulating cosmic ray intensity, while also incorporating recent advancements in understanding solar energetic particle propagation and geomagnetic influences.

2. DATA AND METHODOLOGY

2.1 Data Sources

The empirical foundation of this study relies on continuous datasets spanning the entirety of Solar Cycle 24, from 2008 to 2019. To quantify Galactic Cosmic Ray variations, daily average Cosmic Ray Intensity (CRI) data were extracted from the Oulu Neutron Monitor, which operates at a geomagnetic cutoff rigidity of Rc = 0.81 GV. The corresponding in situ interplanetary conditions was evaluated using high-resolution data from the near-Earth OMNIWeb database. The primary solar wind kinematics extracted include the bulk velocity (V in km/s), proton plasma density (Np in cm^{-3}), and proton temperature (T in K). To evaluate the physical force exerted by the solar wind plasma, the dynamic pressure (P_{dyn} in nPa) was derived using the fluid momentum flux equation:

$$P_{dyn} = N_p \, m_p V^2$$

$$P_{dyn} = \rho V^2$$

where

$\rho = N_p m_p$ is the mass density of the plasma.

The structural magnetic environment driving diffusion was characterized using the total scalar magnitude of the Interplanetary Magnetic Field (B in nT).

2.2 METHODOLOGY

To systematically quantify the physical relationships and temporal modulations between the CRI and these localized solar wind parameters, a robust statistical framework was employed. The primary analytical approach utilized Pearson correlation analysis to evaluate the strength and direction of linear associations between the heliospheric drivers and cosmic ray fluxes. The correlation coefficient r for variables X (solar wind parameter) and Y (CRI) was calculated as:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\left(\sum_{i=1}^{n}(X_i - \bar{X})^2\right)\left(\sum_{i=1}^{n}(Y_i - \bar{Y})^2\right)}}$$

This baseline correlation was supplemented by ordinary linear regression to explicitly model the amplitude of CRI suppression as a function of the varying driver magnitudes. Finally, time-lag analysis and comparative phase analysis were conducted across distinct stages of the solar cycle. These temporal methods allowed for the isolation of delayed recovery profiles, quantifying the hysteresis effect inherent in the heliospheric modulation of cosmic rays as the inner heliosphere reacts to passing transient streams.

3. RESULTS AND DISCUSSION

3.1 Influence of IMF on Long-Term Modulation of CRI

The results clearly demonstrate that the Interplanetary Magnetic Field (IMF) magnitude (B) is the dominant parameter governing long-term modulation of Cosmic Ray Intensity (CRI) during Solar Cycle 24 (2008-2019). A statistically significant inverse relationship is observed, indicating that increases in IMF strength correspond to decreases in CRI. This anti-correlation is consistent with classical cosmic ray modulation theory [24, 25].

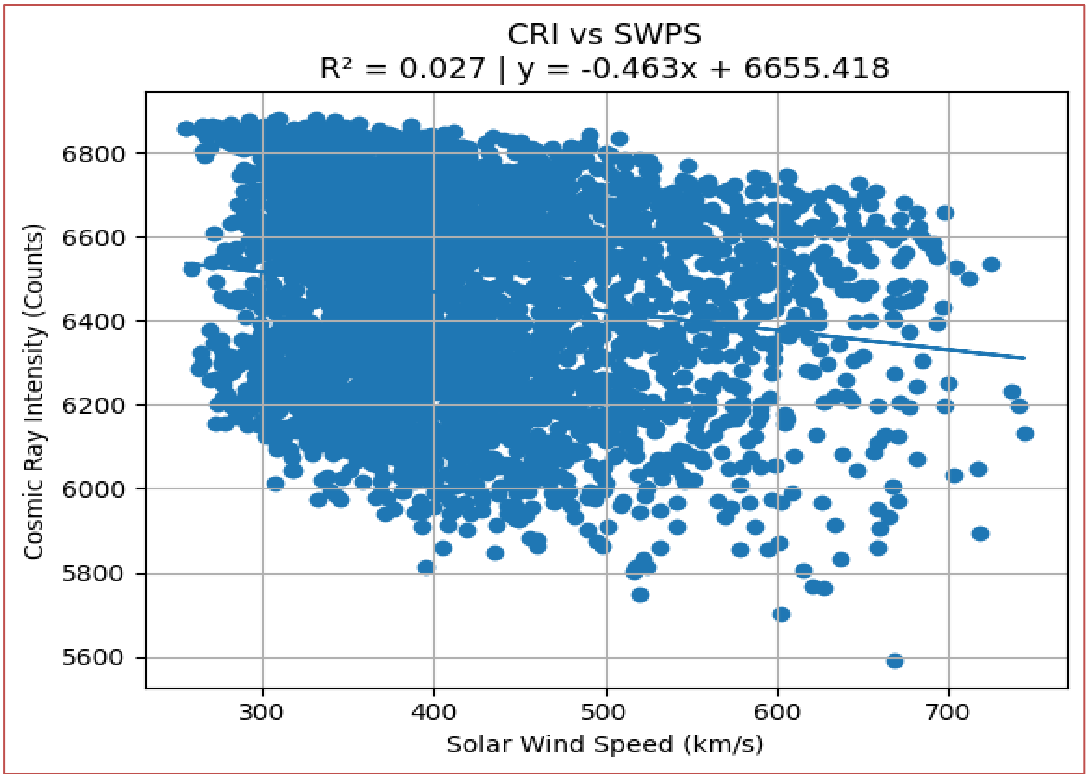

Figure 1. Scatter plot demonstrating the relationship between Cosmic Ray Intensity (CRI) and Solar Wind Proton Speed (SWPS).

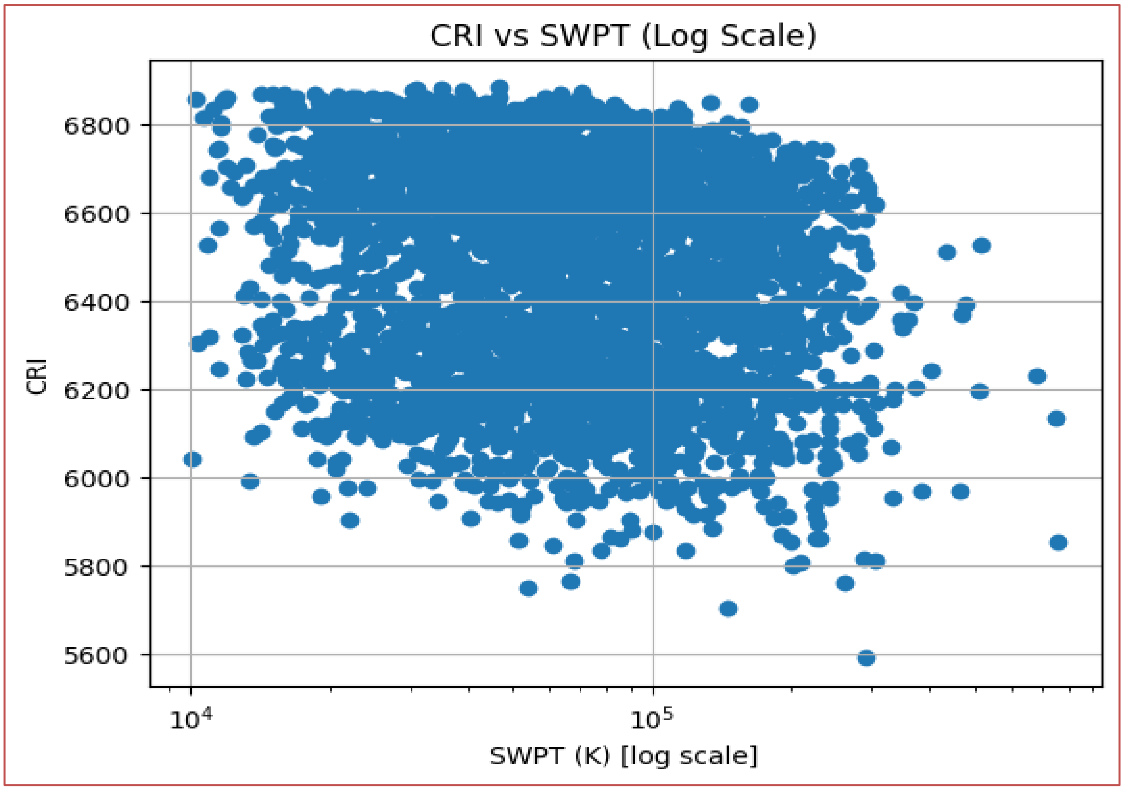

Figure 2. Scatter plot illustrating the relationship between Cosmic Ray Intensity (CRI) and Solar Wind Proton Temperature (SWPT).

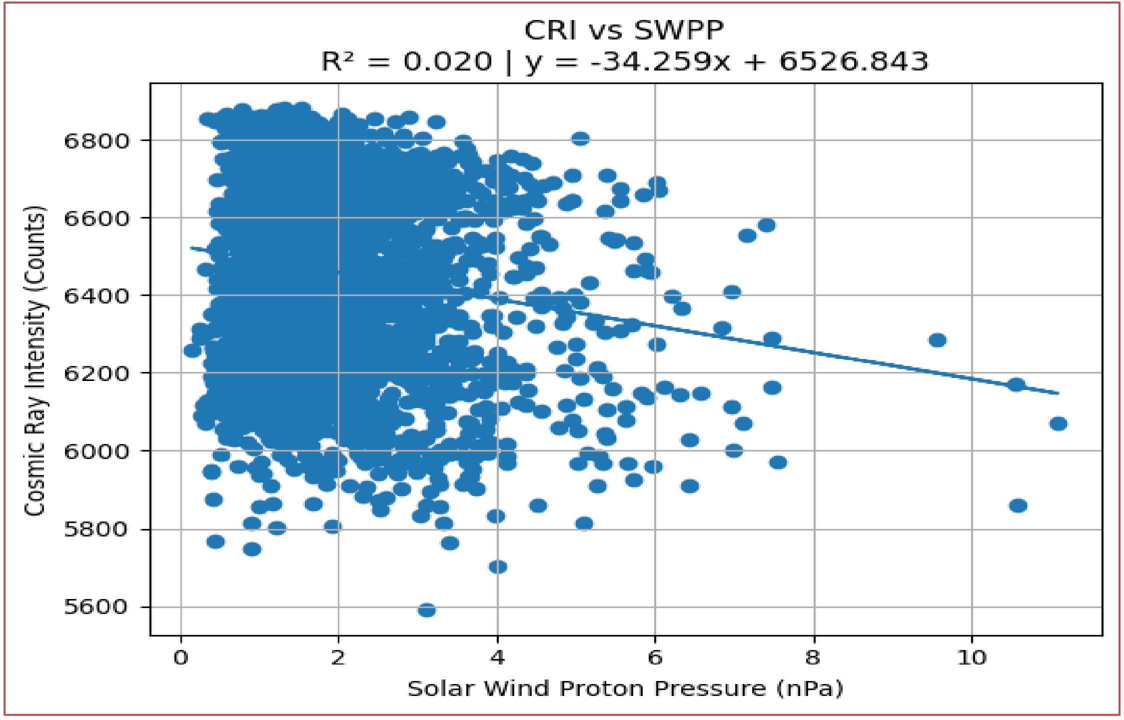

Figure 3. Linear regression analysis correlating Cosmic Ray Intensity (CRI) with Solar Wind Proton Pressure (dynamic pressure).

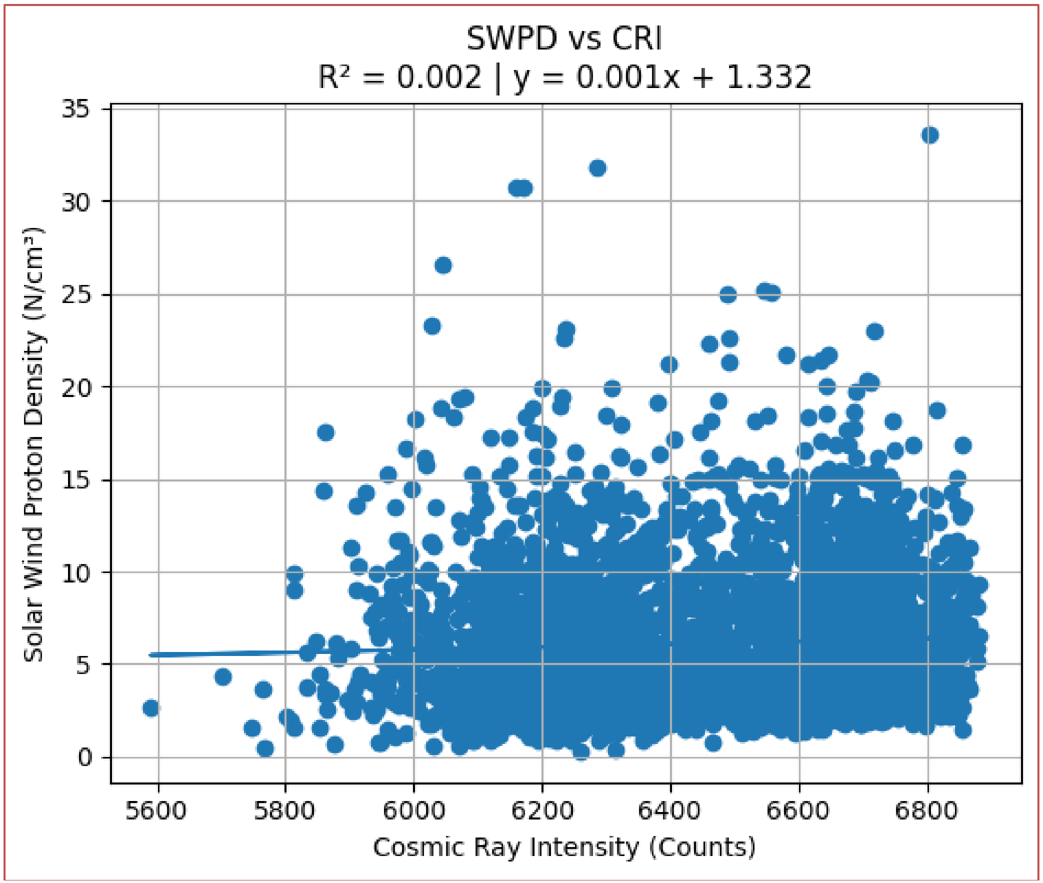

Figure 4. Scatter plot and corresponding linear regression plotting Solar Wind Proton Density against Cosmic Ray Intensity.

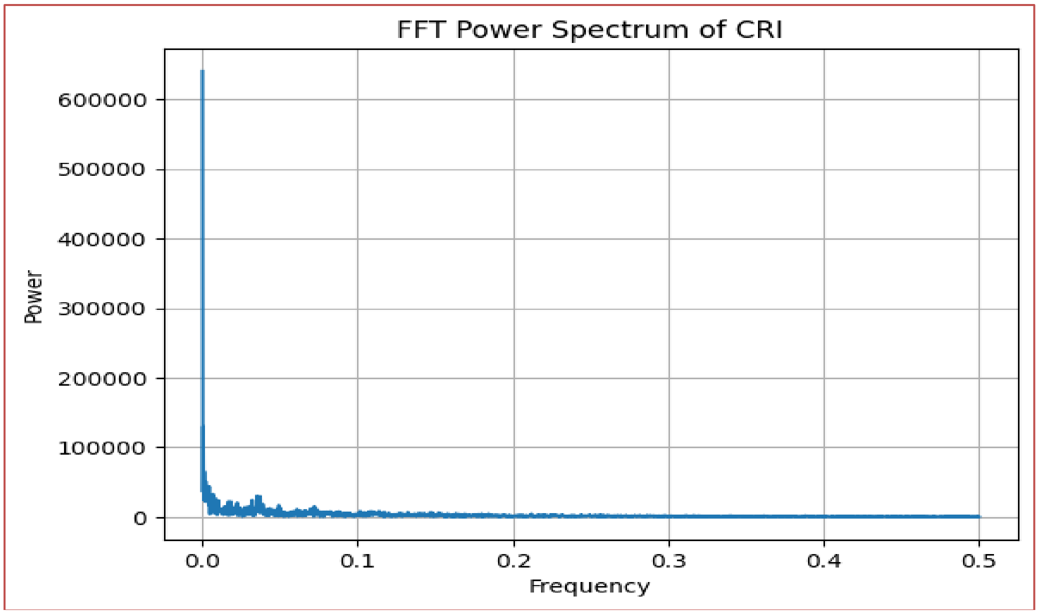

Figure 5. Showing FFT Power Spectrum of Cosmic Ray Intensity (CRI) during Solar Cycle 24. The prominent peak at near-zero frequencies illustrate the overwhelming dominance of long-term periodicities

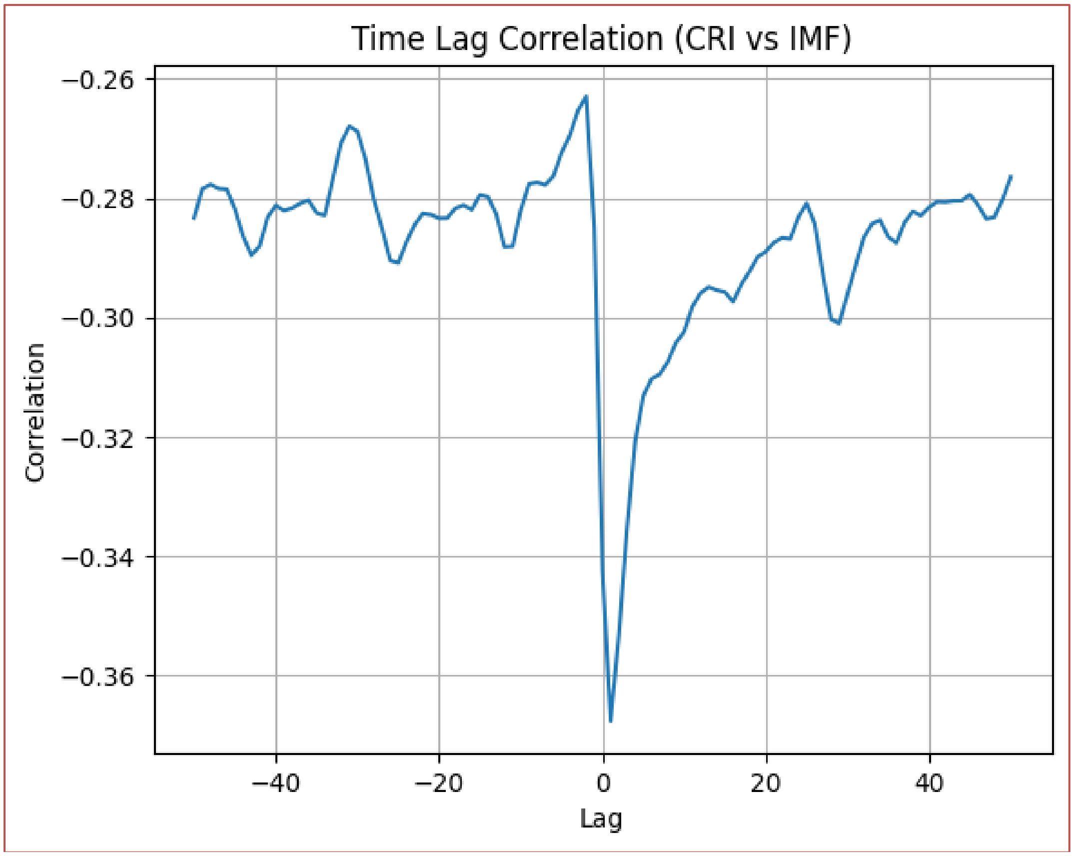

Figure 6. Cross-correlation function between Cosmic Ray Intensity (CRI) and Interplanetary Magnetic Field (IMF) magnitude across varying time lags (in days).

During solar minimum phases (2008-2009 and 2018-2019), IMF values dropped below 4 nT, corresponding to relatively quiet heliospheric conditions. Under these conditions, the diffusion coefficient of galactic cosmic rays increases, allowing enhanced penetration into the inner heliosphere and resulting in higher CRI levels [26]. Conversely, during solar maximum (2013-2015), IMF strength increased to 6-8 nT due to enhanced solar activity, leading to stronger magnetic turbulence and reduced CRI.

This behavior can be explained using the Parker transport equation, which describes cosmic ray propagation through diffusion, convection, drifts, and energy changes [24, 26]. The observed correlation coefficient (r = -0.342) confirms that IMF plays a central role in long-term modulation.

3.2 Relationship Between CRI and Solar Wind Parameters

The influence of solar wind plasma parameters on Cosmic Ray Intensity (CRI) was systematically examined to assess their role in heliospheric modulation processes. The statistical analysis reveals that, although these parameters exhibit some level of correlation with CRI, their overall influence remains comparatively weak when contrasted with the dominant effect of the Interplanetary Magnetic Field (IMF). This indicates that plasma properties primarily contribute to short-term variations rather than long-term modulation.

(a) Solar Wind Speed (Vsw)

Figure 1 shows a weak negative correlation between CRI and solar wind speed (r = -0.164), suggesting that increases in solar wind velocity are associated with slight reductions in cosmic ray intensity. High-speed solar wind streams, particularly those originating from coronal holes, enhance the convective outward transport of charged particles, thereby opposing the inward diffusion of galactic cosmic rays. These streams can also interact with slower solar wind regions to form Corotating Interaction Regions (CIRs), which act as diffusion barriers. However, the relatively low correlation coefficient indicates that solar wind speed alone is insufficient to significantly control long-term CRI modulation. Its contribution is largely indirect and becomes more prominent during transient events such as recurrent high-speed streams [27].

(b) Solar Wind Proton Temperature (SWPT)

Figure 2 indicates a weak inverse relationship between CRI and solar wind proton temperature. Elevated proton temperatures are generally indicative of enhanced solar wind energy and increased levels of turbulence within the heliosphere. Such turbulent conditions can contribute to increased scattering of cosmic rays, thereby reducing their effective diffusion into the inner heliosphere. However, proton temperature is not a primary parameter in cosmic ray transport equations and instead reflects underlying plasma conditions. As a result, its influence on CRI remains indirect and limited, as supported by its weak statistical correlation [28].

(c) Dynamic Pressure (Pdyn)

Figure 3 presents a weak negative correlation between CRI and solar wind dynamic pressure (r = -0.141). Dynamic pressure, which depends on both solar wind density and velocity, represents the momentum flux of the solar wind. Increased dynamic pressure leads to compression of the heliospheric magnetic field and can enhance local magnetic field strength, thereby increasing the scattering efficiency of cosmic rays. This compressional effect can temporarily reduce CRI, particularly during interplanetary disturbances such as shocks and ICMEs. However, the low coefficient of determination indicates that this parameter contributes only marginally to long-term modulation, acting primarily during episodic events [29].

(d) Proton Density (Np)

Figure 4 reveals an almost negligible positive correlation between proton density and CRI (r = +0.045), indicating that density variations have minimal direct impact on cosmic ray propagation. Although proton density contributes to solar wind dynamic pressure, it does not directly influence magnetic field topology or turbulence levels, which are the primary drivers of cosmic ray modulation. The weak and nearly insignificant correlation suggests that proton density plays a passive role and is not a controlling factor in the modulation process.

Overall, these results confirm that solar wind plasma parameters while important for understanding transient heliospheric disturbances do not significantly influence long-term cosmic ray modulation. Their effects are largely secondary and often mediated through their interaction with the heliospheric magnetic field. This conclusion is consistent with established modulation theory, which emphasizes the dominant role of magnetic field strength and turbulence over plasma properties [26].

3.3 Spectral Characteristics of CRI Variability

The Fast Fourier Transform (FFT) power spectrum of CRI, shown in Figure 5, exhibits a pronounced peak at near-zero frequencies, indicating the dominance of long-term periodic variations. This spectral feature corresponds to the well-known ~11-year solar cycle, which governs large-scale changes in heliospheric conditions, including IMF strength, solar wind structure, and magnetic turbulence.

The concentration of spectral power at low frequencies suggests that CRI variability is primarily driven by gradual, large-scale processes rather than short-term fluctuations. The absence of significant high-frequency peaks further indicates that transient events such as Forbush decreases, while impactful on short timescales, contribute only minimally to the overall variance in CRI. These findings reinforce the conclusion that cosmic ray modulation is largely controlled by solar cycle–dependent changes in heliospheric structure and magnetic field intensity [26, 30].

Additionally, the spectral smoothness implies a stable and continuous modulation process, rather than sporadic or random variations, highlighting the deterministic influence of solar activity cycles on cosmic ray intensity.

3.4 Temporal Response of CRI to IMF Variations

The cross-correlation analysis presented in Figure 6 provides important insight into the temporal coupling between CRI and IMF magnitude. The results reveal a strong anti-correlation, with peak correlation occurring at small time lags, typically within the range of 0-3 days. This indicates that cosmic ray intensity responds rapidly to changes in heliospheric magnetic field conditions.

Such a short response time suggests that cosmic ray transport is highly sensitive to variations in magnetic field strength and turbulence levels. The near-immediate reaction can be attributed to efficient diffusion processes, where changes in magnetic irregularities quickly alter the propagation environment for charged particles. Furthermore, the minimal lag implies that local interplanetary conditions near Earth play a critical role in determining observed CRI levels.

This behaviour is consistent with diffusion-dominated transport models, where the modulation of cosmic rays is governed by rapid adjustments in scattering conditions rather than delayed large-scale processes. The results also support theoretical predictions that emphasize the importance of magnetic field fluctuations in controlling cosmic ray access to the inner heliosphere [25, 26].

Table 1: Linear Regression Summary for CRI vs. Solar Wind Parameters (2008–2019)

Heliospheric Parameter	Regression Equation	Variance (R^2)	Correlation (r)
Interplanetary Magnetic Field (B)	y = -38.147x + 6665.256	0.117	-0.342
Solar Wind Speed (Vsw)	y = -0.463x + 6655.418	0.027	-0.164
Solar Wind Dynamic Pressure (Pdyn)	y = -34.259x + 6526.843	0.020	-0.141
Solar Wind Proton Density (Np)	y = 0.001x + 1.332	0.002	+0.045

3.5 Statistical Interpretation of Regression Results

The regression analysis provides a quantitative framework for evaluating the relative influence of heliospheric parameters on Cosmic Ray Intensity (CRI) during Solar Cycle 24. The results clearly indicate that among all considered variables, the Interplanetary Magnetic Field (IMF) magnitude (B) exhibits the strongest statistical relationship with CRI, with a negative correlation coefficient of r = -0.342 and the highest coefficient of determination (R^2 = 0.117). This moderate inverse correlation confirms that increases in IMF strength are consistently associated with reductions in cosmic ray intensity, reinforcing the dominant role of magnetic field conditions in governing long-term modulation processes. Despite being the strongest among the analysed parameters, the relatively low R^2 value for IMF suggests that only about 11.7% of the variance in

CRI can be explained by IMF variations alone. This highlights the inherently complex and multi-dimensional nature of cosmic ray modulation, where multiple physical processes operate simultaneously and nonlinearly. The remaining unexplained variance is likely attributed to additional factors such as magnetic turbulence spectra, particle drift effects, heliospheric current sheet structure, and temporal variations in solar activity.

Solar wind speed (Vsw) and dynamic pressure (Pdyn) both exhibit weak negative correlations with CRI, with correlation coefficients of $r = -0.164$ and $r = -0.141$, respectively, and correspondingly low R^2 values (0.027 and 0.020). These results indicate that although increases in solar wind speed and pressure can contribute to a reduction in CRI primarily through enhanced convection and temporary compression of the heliosphere their overall contribution to long-term modulation is minimal. Their influence is more prominent during transient events such as high-speed streams, shocks, and interplanetary coronal mass ejections (ICMEs), rather than in steady-state modulation. In contrast, proton density (Np) shows an almost negligible positive correlation with CRI ($r = +0.045$, $R^2 = 0.002$), indicating that density variations have virtually no direct statistical significance in controlling cosmic ray intensity. This further supports the conclusion that plasma density, while contributing to dynamic pressure, does not directly influence the magnetic field configuration or turbulence levels that govern cosmic ray transport.

An important implication of these findings is that linear regression models alone are insufficient to fully describe cosmic ray modulation. The low R^2 values across all parameters suggest that the relationship between CRI and heliospheric variables is inherently nonlinear and influenced by coupled physical processes. These include magnetic turbulence, which affects particle scattering; gradient and curvature drifts, which depend on large-scale magnetic field geometry; and the evolving structure of the heliosphere over the solar cycle.

Furthermore, the statistical dispersion observed in the regression plots indicates the presence of time-dependent effects such as hysteresis between solar activity and CRI response, as well as phase differences between solar wind parameters and cosmic ray intensity. This reinforces the need for more advanced modelling approaches, such as time-lagged regression, nonlinear modelling, or numerical solutions of transport equations, to better capture the complexity of cosmic ray modulation. Overall, the regression analysis confirms that while IMF is the primary controlling parameter, cosmic ray modulation cannot be attributed to a single variable. Instead, it results from the combined and interdependent effects of multiple heliospheric processes, including magnetic field strength, turbulence, particle drifts, and solar cycle driven structural changes in the heliosphere [26, 28].

3.6 Physical Interpretation and Discussion

The results strongly support the theoretical framework in which cosmic ray modulation is primarily governed by heliospheric magnetic field conditions, with the Interplanetary Magnetic Field (IMF) playing a dominant role. This influence can be understood through several key physical processes acting simultaneously within the heliosphere. First, diffusion occurs as cosmic rays scatter off magnetic irregularities; an increase in IMF strength enhances magnetic turbulence, which reduces the diffusion coefficient and limits the inward transport of particles. Second, convection driven by the outward-flowing solar wind carries cosmic rays away from the inner heliosphere, thereby opposing their inward propagation, and this effect becomes more pronounced during periods of high solar activity. Third, charged particles undergo gradient and curvature drifts in the large-scale heliospheric magnetic field, with the magnitude and direction of these drift motions depending on the solar cycle polarity and the strength of the magnetic field. Finally, adiabatic energy losses occur as cosmic rays propagate through the expanding solar wind, leading to a gradual reduction in their energy and consequently their observed intensity near Earth. During solar maximum, all these modulation processes intensify due to enhanced magnetic field strength and turbulence, resulting in a significant suppression of Cosmic Ray Intensity (CRI). In contrast, during solar minimum, the relatively weak and less turbulent magnetic field conditions allow galactic cosmic rays to penetrate more efficiently into the inner heliosphere, leading to higher observed CRI levels.

4. CONCLUSION

The present study provides a comprehensive analysis of the long-term modulation of Cosmic Ray Intensity (CRI) in relation to heliospheric conditions during Solar Cycle 24 (2008-2019). The results clearly establish that the Interplanetary Magnetic Field (IMF) magnitude is the most influential parameter governing CRI variability, exhibiting a consistent and physically meaningful inverse relationship. Periods of low IMF strength during solar minimum correspond to enhanced cosmic ray flux, whereas elevated IMF conditions during solar maximum significantly suppress CRI. This behavior confirms the fundamental role of heliospheric magnetic fields in regulating the transport of galactic cosmic rays.

In comparison, solar wind plasma parameters including solar wind speed, dynamic pressure, proton temperature, and density show relatively weak or negligible correlations with CRI. Although these parameters contribute to short-term and transient modulation effects, their impact on long-term cosmic ray variability is secondary. This distinction highlights the dominance of large-scale magnetic field structures and turbulence over local plasma properties in controlling cosmic ray propagation.

Spectral analysis further demonstrates that CRI variability is dominated by long-term periodicities associated with the 11-year solar cycle, with minimal contribution from high-frequency fluctuations. The cross-correlation results indicate that CRI responds rapidly to changes in IMF conditions, suggesting efficient and diffusion-dominated transport mechanisms within the heliosphere.

The findings are consistent with established cosmic ray modulation theory, where diffusion, convection, particle drifts, and adiabatic energy losses collectively regulate particle transport. During solar maximum, enhanced magnetic turbulence and stronger IMF intensify these processes, leading to reduced cosmic ray penetration. Conversely, during solar minimum, weaker magnetic fields allow greater access of galactic cosmic rays to the inner heliosphere.

Overall, this study reinforces the understanding that heliospheric magnetic field dynamics are the primary drivers of cosmic ray modulation near Earth. The results not only validate theoretical models but also contribute to improved prediction of cosmic ray variability, which is crucial for space weather studies, satellite operations, and radiation risk assessment in space exploration.

Acknowledgement

The authors acknowledge NASA OMNIWeb for solar wind data and the Oulu Neutron Monitor for cosmic ray data. We also thank NOAA and NGDC for providing solar and geomagnetic datasets.

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